Army Research Laboratory

Multi-Core Computing Cluster for Safety Fan Analysis of Guided Projectiles

by Mark Ilg

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14. ABSTRACT

During the design phase of Guidance, Navigation, and Control (GN&C) systems for guided projectiles, performance evaluation of the algorithms, and the resulting flight dynamics, is invaluable. In order to characterize the performance of a system's effectiveness, a Monte Carlo analysis is typically performed using empirically derived random variable distributions. Due to the complexity of the GN&C system, typical methods of linearization and closed form solution evaluation do not provide adequate results when determining the key parameters for measuring overall system performance. Since reliance on traditional methods is not adequate, Monte Carlo analysis must be performed with thousands, if not hundreds of thousands of iterations. Analysis of this complexity requires significant computational assets, therefore this process is used sparingly during the design phases. However, determining the true robustness of a control system cannot be resolved without performing this critical analysis. Through parallelization, this process can be run independently on many processors simultaneously, reducing the run time and allowing for quick evaluation of design modifications and algorithm updates. By using a small computing cluster and rapidly parallizing simulations, the Monte Carlo analysis can be integrated into the design cycle and mitigate errors prior to costly flight experiments. This rapid analysis provides a critical tool, not only for the evaluation of the system performance, but for safety fan analysis as well.

15. SUBJECT TERMS

GN&C, computing cluster, Monte Carlo, safety fan

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1. Introduction

The greatest challenge facing the Army as it transitions from conventional ammunition to systems capable of highly precise delivery is cost, driven by complexity. To meet increasingly demanding precision requirements, the complexity of the solutions can grow exponentially. This tremendous growth in system complexity was accompanied by dramatically increasing demands on our modeling and simulation (M&S) environments, without which the Army would be unable to predict performance, which would ultimately impact the battlefield. The escalation of these problems has quickly exceeded the ability of our traditional M&S tools and require a new and truly multidisciplinary approach, integrating expertise across key areas to include fluid dynamics, aerodynamics, guidance laws, control theory, flight dynamics, microelectronics, mechanical design, and statistical methods. To address these challenges a Model Based Design (MBD) approach has been used to maintain a work environment that adapts to the ever-changing physical aspects of the system. This methodology was used in the design of a Guidance, Navigation, and Control (GN&C) system for the Very Affordable Precision Projectile (VAPP) demonstration program and now the Flight Controlled Mortar (FCMortar). Both of these systems consist of a reduced state guidance methodology that exploits the ballistic flight dynamics, ultimately requiring fewer sensors, of lower accuracy and cost, to provide a quality navigation solution.

To evaluate the effectiveness of a GN&C system, a complete analysis of the system must be performed. With the prevalence of high throughput computing, the process of evaluating the GN&C system during the design phase becomes more economically feasible. To evaluate the effectiveness of the GN&C system, high fidelity simulations are performed to ensure accurate representation of the physical system.

A complete set of advanced aerodynamic prediction tools was used throughout the design and development process to establish aerodynamic performance and optimization. These results were fed into a flight control system simulation developed by the U.S. Army Research Laboratory (ARL). Using the Precision Simulation Environment (PRESIMEN), which includes a design environment, hardware/processor-in-the loop (HIL/PIL) system, and computing cluster, the GN&C system can be fully evaluated and tested. The MBD is significantly different from traditional design processes and begins with a plant model based on the projectile aerodynamics and physical properties, consisting of recursive steps and model refinement loops, each of which is rapidly integrated into the PRESIMEN environment. Thus, the computing cluster must inherit the framework inherent in the full design process including the HIL and PIL setups.

The testing and verification process is improved because the entire design life cycle is fluid and does not require significant changes mid-cycle. The dynamic effects on the system are rapidly identified through the HIL testing much more efficiently than with tradition design methodology, and problems can be identified early before costly flight testing. To provide scalable effects, the Army has requested the VAPP in various form factors including 105mm artillery, 120mm mortar, and 155mm artillery. A similar path for the 81mm FCMortar is anticipated. Though the applications are extremely different, the use of MBD allows the porting of control system algorithms from one system to the next with little to no code changes. Through the use of a common interface for each of the calibers, aerodynamic updates and simulations were performed within days of having new data available. This rapid integration into the simulation environment, HIL/PIL, and computing cluster allowed for quick evaluation of the control system and analysis of the performance. Without the design process in place, this would not have been feasible with such a small engineering team and under the severely constrained timeline. The result of the MBD approach for the VAPP allowed the engineering team to design, evaluate, and implement a GN&C control system. This effort culminated two test firing events, the VAPP 120mm mortar at Aberdeen Proving Ground (APG), MD, in February 2009 and the VAPP 155mm artillery at Yuma Proving Ground, AZ, in July 2010. The success of the VAPP 120mm mortar program spurred the rapid development of the VAPP 155mm artillery, and within months, the design process was complete including all relevant sub-tests and design modifications. The VAPP 155mm test firing demonstration proved to be a successful finale to the entire model-based approach within the year of the program initiation. The fact that all critical intellectual property was developed and owned by the government represents a significant step towards truly affordable precision for the Army. The rapid deployment of GN&C algorithms and system design has never been accomplished within the government prior to this program.

This report outlines the design process and construction of the computing cluster. Results of Monte Carlo testing of the FCMortar projectile are presented to show the scalability of the code to multiple processors and the computing time required. A description is included on the modeling and simulation environment used in the design process and the use of commercial/open source computing software for rapid development of the capability. The results demonstrate how the MBD approach to the design cycle is an effective tool for rapidly developing control system algorithms and for validating the design with limited resources while still maintaining a rigorous and thorough design process. This design process is culminated in a representative safety fan analysis for the FCMortar. A proposed method for handling the results of the Monte Carlo analysis is proposed and the results are obtained using the computing cluster.

2. Projectile Description

2.1 Aerodynamics Model

The model used in the simulation and Monte Carlo analysis of the projectile dynamics is depicted in the block diagram outlined in figure 1.

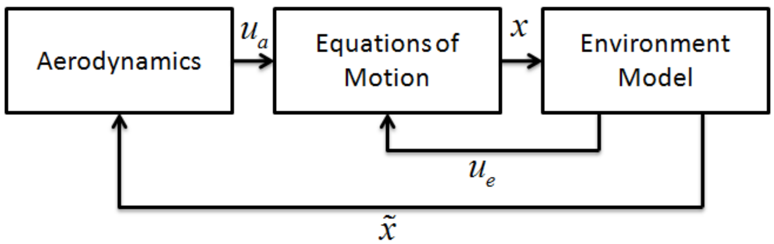

Figure 1. Block diagram of the model.

Note:

u_a	Aerodynamic Forces and Moments
u_e	Environmental Forces and Moments
x	State Vector
$\tilde{x}$	Environmentally Perturbed State Vector

2.1.1 Equations of Motion

The state equations for the equations of motion block are shown in equations 1–4. Equations 1 and 2 are the Translational and Rotational Dynamic equations for a rigid body, respectively.

$$\dot{V} = \frac{F_b}{m} - \omega \times V \tag{1}$$

$$\dot{\omega} = I^{-1} \left(M_b - \omega \times I\omega \right) \tag{2}$$

where

V	=	body fixed velocity vector
F_b	=	applied forces
ω	=	body fixed angular rates
m	=	mass of the projectile
I	=	inertia tensor
M_b	=	applied moments

The applied forces consist of the body and canard aerodynamic forces and force due to gravity. The applied moments consist of the body and canard moments and the moment due to the center of gravity offset. In the simulation, the aerodynamic forces and moments consist of lookup tables derived through empirical methods, computational fluid dynamics (CFD), wind tunnel experiments, and flight experiments. The remaining state variables consist of the kinematic equations:

$$\dot{X}_e = R^{-1}V \tag{3}$$

$$\dot{\mathbf{q}} = [\omega]_{\times}\mathbf{q} \tag{4}$$

where X_e is the position of the projectile in the reference coordinate system, R is the direction cosine matrix, and $\mathbf{q}$ is the quaternion, and $[\bullet]_{\times}$ represents the skew symmetric matrix product. Although quaternion representation is used in this simulation, Euler angles, or direction cosine matrix state propagation could be used. Derivation of the equations of motion has been extensively studied in references *1–6*. The aerodynamic model also includes the following sub-models, which will not be detailed: wind models, a gravity model, a temperature model, and a pressure model.

2.1.2 Simulink Model

To implement the mathematical model, Simulink^{TM} was chosen as the main method for integration of the orginary differential equation (ODE) equations. The model block diagram is shown in figure 1. Implementation in Simulink^{TM} was chosen for simulation completeness, ease of migration into the HIL/PIL system setups, and ODE solver solutions. A feature released in Matlab^{TM} 2008a, Rapid Accelerator Mode, allows for Simulink^{TM} model compilation using Mathworks Real-Time Workshop (RTW) to build standalone executable models. The standard Matlab^{TM} Simulink^{TM} flow is shown in figure 2(a), where Matlab^{TM} handles the base workspace data and control. Simulink^{TM} is deeply integrated into the Matlab^{TM} interface and the simulation control routines and settings can be directly configured from the base Matlab^{TM} frontend.

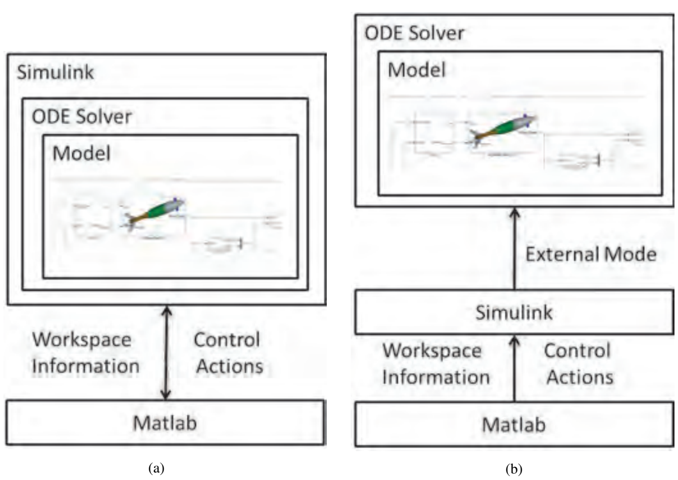

Figure 2. Matlab^{TM} Simulink^{TM} RSim connections.

The Rapid Accelerator Mode (RSim) goes one step further to optimize the execution time of the Simulink^{TM} model by creating a standalone executable and connecting to the executable via the External Mode interface, as shown in figure 2(b). This abstraction allows the executable to run as a separate process, potentially on another core. This compilation and execution allows for a significant performance increase in the execution time of the model. Typical performance increases for a six-degrees-of-freedom (6DOF) executable can improve run times from 60 s to 5 s or less showing a >12x increase in speed. This speedup obviously depends on model complexity, compilation optimizations, and computing resources on the host machine.

To fully use the Simulink^{TM} model, compilation to the RSim for the computing cluster must be completed. Since the RSim method requires compilation of the Simulink^{TM} model, access to the workspace variables would be eliminated. This bidirectional interface is critical for performing the Monte Carlo analysis. During the design phase of the GN&C system, we would like to vary many of the parameters within the model to ensure robustness of the GN&C systems. To preserve the ability to update the critical parameters during the trade study design phase, the Simulink^{TM} model must be adapted to allow for these parameters to be passed as arguments to the standalone executable.

The process of parameterizing the model is outlined in figure 3. From the block diagram of figure 3, we show how the Matlab^{TM} base engine communicates with the Simulink^{TM} and RSim models. RSim models only support inline parameters of certain types. Since most of our model parameters are in structure formats to preserve naming conventions, each structure argument that is to be parameterized must be converted to a supported type. This operation is performed during the Search and Replace phase of the operation. Once the arguments are converted to a proper format, the Real Time Parameter (RTP) structure is configured for inline parameters. This setting provides a means of passing command line arguments to the RSim model and preserving the parameters within the compiled executable. To generate the Monte Carlo parameters, the parameter list is passed through a function to use the built-in random number generator to compute the required parameter values lists within the RTP structure. Examples of the Monte Carlo distribution generation are described in section 4. Through this process the standalone executable is configured to read in a corresponding RTP structure and compute the 6DOF results based on the stimuli. Without model parameterizations and inlining, the RSim model would not be able to vary any of the model parameters.

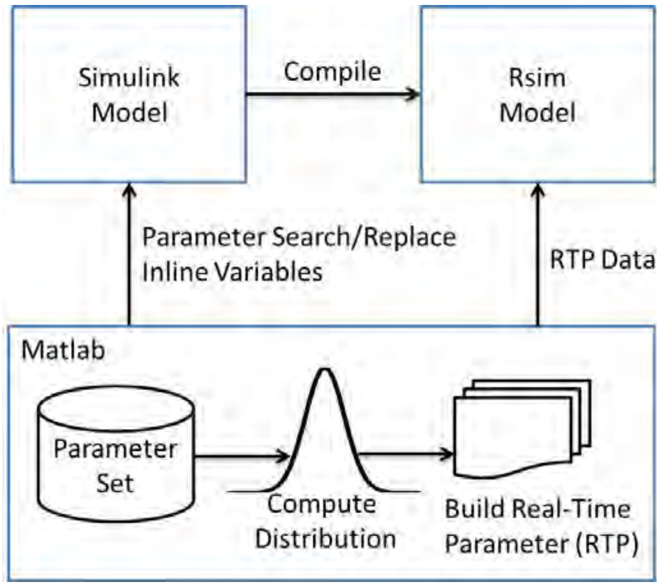

Figure 3. Simulink™ to RSim process.

3. Cluster Configuration

With the capability of using Simulink™ models as standalone executables, we can now extend the Matlab™ Simulink™ Model as compiled by the RTW to cluster scale for higher throughput. During the process of GN&C design of complex nonlinear systems, Monte Carlo analysis is the defacto standard. To perform enough simulations at each iteration of the design would be infeasible on a standard laptop or computer. Because of the run times associated with many of the projectile 6DOF models, full Monte Carlo analysis was typically not performed. This can add variability in the understanding of the performance and characteristics of the design. To address these issues and to speed up development, we have used standard hardware available in the laboratory and augmented the systems with a open source scheduler, Condor. The Condor Project is a workload management system developed by the University of Wisconsin-Madison. The scheduler is ideal for this type of application of serial processes and can operate on the "wasted" CPU time of the host computers. In our current configuration, we have a dedicated 40-core system connected through a local 100-MB ethernet. This setup provides sole use of the processors for the Monte Carlo analysis.

Figure 4 shows the basic setup of the computing cluster at APG, MD, used in the analysis of GN&C systems. The host system connects to the computing cluster via the local ethernet network. The required files for the running of the RSim model are copied to the computing cluster and initiated through the Condor scheduler.

Figure 5 shows the work flow of running the computing cluster. As shown, the host computer compiles the RTP structure, generates a Condor run script, copies the RSim executable and RTP.mat file to the cluster, and executes the Condor script. After the completion of the batch runs, Condor notifies the host computer, and all data are copied back to the host computer for processing and analysis.

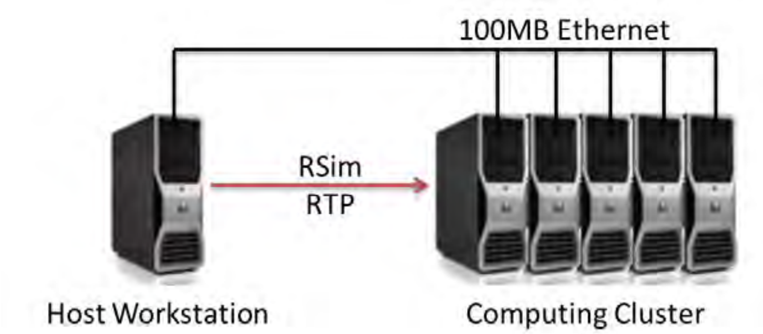

Figure 4. Block diagram of the model.

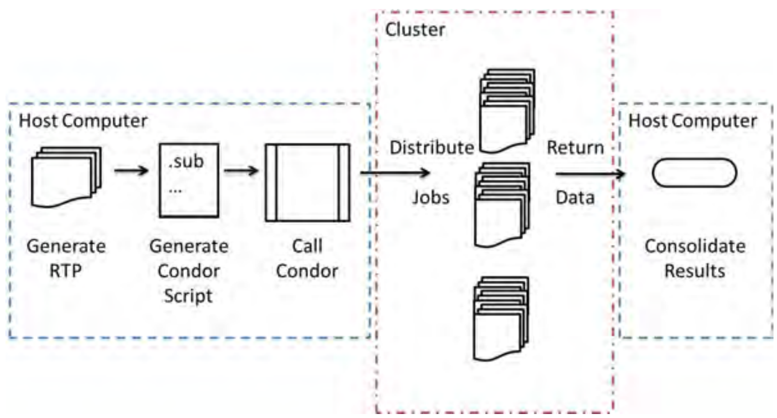

Figure 5. Flow diagram of the running model.

3.1 Monte Carlo Setup

In order to provide adequate results from the computing cluster, proper models of the aerodynamic terms, environment, GN&C parameters, and mass properties must be used. Data sets using a variety of historical data are used in the computation of the random variance on these parameters. Using the Matlab™ environment, we can use the built-in random number generator, which uses the Marsaglia and W. W. Tsang psuedorandom number generator (*7*). This random number generater is based on a uniform distribution and alternate distributions are computed based on a transformation. Some typical probability distribution functions used in the modeling of the above parameters are Uniform, Gaussian, Raleigh, Binomial, and Integer. For the Monte Carlo analysis of the projectile, we vary the parameters based on the probability distribution function (PDF) and simulate the nonlinear dynamics.

4. Monte Carlo Analysis

The proposed application of the computing cluster is computing the safety fan for test firings. Typically with unguided munitions, with limited system complexity, simple three-degrees-of-freedom (3DOF) models can be used to predict the impact envelope of the projectile; this is not the case with guided munitions. As a tool to ensure safety, many Monte Carlo runs are exercised with introduced failure modes and parameter variance. When the results of the Monte Carlo analysis converge, we can make more educated judgement on the safety requirements at the range. To exercise the computing cluster, a safety fan analysis was conducted for a guided FCMortar projectile.

4.1 Parameter Distributions

Tables 1–3 show the parameters used in the exercise. In table 1, the parameters are varied using an additive normal distribution. For example, the mass used in each draw of the Monte Carlo, m_{Monte}, equals the nominal mass plus a normally distributed random variable with mean zero and a variance of 0.14507 kg. Tables 2 and 3 use the same convention. The tables are a limited subset of all of the parameters that can be varied using the computing cluster environment and are displayed for comprehensiveness.

Table 1. Additive normal distribution: $x_{Monte} = x_{Base} + \mathcal{N}(\mu, \sigma)$.

	Mean μ	Standard Deviation σ	Units
Mass	0	0.14507	kg
Inertia I_{xx}	0	0.000587	kg/m^2
Inertia $I_{yy,zz}$	0	0.019754	kg/m^2
Diameter	0	0.000180657	m
Canard Deploy Time	0	1	s
Mean Wind	0	10	m/s
Ground Temperature	0	50	Kelvin
Ground Pressure	0	15000	Pa
Position $Pos_{x,y,z}$	$[0, 0, 0]$	$[0.01, 0.01, 0.01]$	m
Velocity $Vel_(x, y, z)$	$[0, 0, 0]$	$[3.7, 0, 0]$	m/s
Angular Rates $\omega_{x,y,z}$	$[0, 0, 0]$	$[3.7, 0.0001, 0.0001]$	rad/s
ϕ	0	0	rad
θ	0	0.004	rad
ψ	0	0.0054	rad

Table 2. Multiplicative normal distribution: $x_{Monte} = x_{Base} * \mathcal{N}(\mu, \sigma)$.

	Mean μ	Standard Deviation σ
C_{x0}	1	0.01
$C_{N\alpha}$	1	0.05
$C_{YP\alpha}$	1	0.25
$C_{M\alpha}$	1	0.02
C_{Mq}	1	0.15
C_{Lp}	1	0.05

Table 3. Uniform distribution: $x_{Monte} = \mathcal{U}(min, max)$.

	Minimum	Maximum	Units
Canard Phase Angle	0	2π	radians
Wind Angle	0	2π	radians

4.2 Impact Points for System Performance Analysis

The computing cluster was exercised using the tables in section 4.1 for 20k runs on the computing cluster. The host computer is running Windows Vista x64, using Intel®Core™2 Duo T9550 CPU at 2.66 GHz, 8 GB RAM, and Matlab™ 2010b. The cluster PCs are running Windows Vista x64, using Intel®Xeon®X5472 CPU at 3.00 GHz x2, and 2 GB RAM.

Figure 6 shows the three-dimensional (3-D) histogram of the impact points of the guided round. For this simulation, the mortar was shot using an open loop command of full maneuver authority in all directions using a Zone 4 charge. The initial conditions are summarize in the table 4. As shown, the impacts of the runs are scattered based on the draw for each Monte Carlo run. The ODE configuration settings for these particular runs is a 4th-order fixed step Runge-Kutta with a time-step of 500 μs.

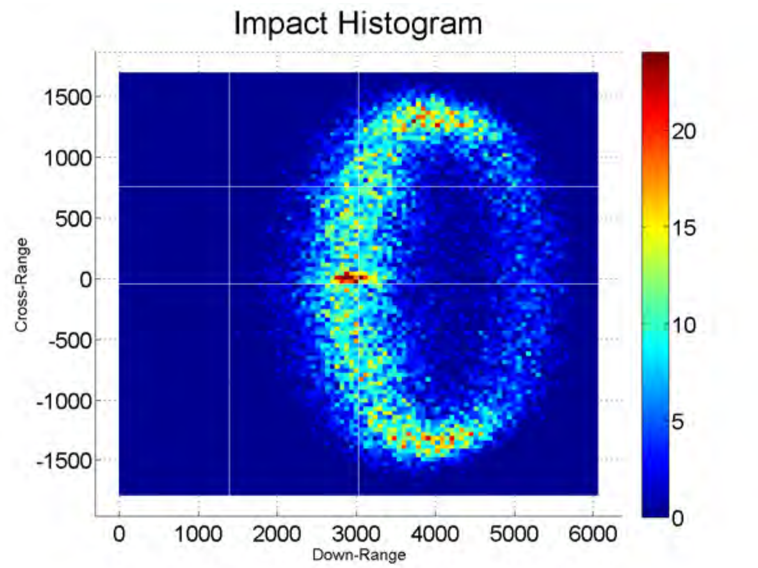

Figure 6. Histogram of the 20k Monte Carlo runs.

Table 4. Mean initial conditions.

Position	$Pos_{x,y,z}$	$[0, 0, 0]$m
Velocity	$Vel_{x,y,z}$	$[274.0, 0, 0]$m/s
Angular	Rates $\omega_{x,y,z}$	$[0, 4.0, 4.0]$rad/s
Euler Angles	$[\phi, \theta, \psi]$	$[0, 56.2500, 0]$ deg

The run times on the computing cluster for 20k runs are shown in figure 7. As displayed, the cluster run times have a mean of approximately 13.02 s.

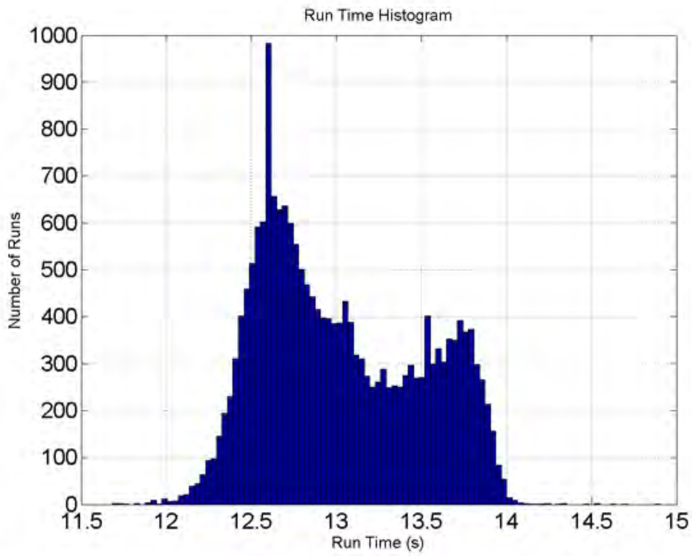

Figure 7. Histogram of the 20k Monte Carlo run times.

The exact same model was run in native Simulink$^{\mathrm{TM}}$ with similar configurations. Table 5 shows some of the results obtained using the standard Simulink$^{\mathrm{TM}}$ routines. The mean of the standard Simulink$^{\mathrm{TM}}$ runs is 26.24 s. Although this is a small subset of the number of runs, it demonstrates the approximately 2 times speedup from the use of the cluster. Alternate means of speedup include the choice of an adaptive ODE solver and constraint selection. With the 2 times speedup and the overhead, the computed run time for the 20k runs on the 40-core cluster is 108.56 min, an extreme improvement over the standalone computation on the base computer of 8748.1 min or 145.80 h.

Table 5. Standard Simulink$^{\mathrm{TM}}$ run times.

Ballistic Simulation	24.9733 s
Maximum Divert Long	30.6558 s
Minimum Divert Short	23.1036 s

4.3 Failure Modes

Section 4.2 outlined the use of the cluster to evaluate the performance of the projectile. During the development stage of the projectile, many of the subsystems are not fully mature, so we must analyze the effect on the system of some of the failure modes that may exist. Some examples of common system failures are fin deployment problems, actuation system failures, guidance system failures, etc. We must incorporate the perceived probability of failure of each of these systems in our simulations to ensure that the safety fan calculation accurately represents all of the possible impact points of the projectile.

These failure modes can all be parameterized within the Monte Carlo construct to provide a means for evaluating the effect of these failures. Figure 8 represents a worst-case scenario for the failure of the GN&C electronics state machine, electronics, and controller. As it is shown from figure 8, there is a potential for the projectile to go behind the gun system and potentially cause catastrophic events. To calculate the probability of the occurrence of this failure, we can use the Monte Carlo results, coupled with the probability of these failures to estimate the probability of occurrence as summarized by equation 5:

$$P_{cat} = P_i * P_s * P_c * P_e \tag{5}$$

This particular example shows the probability of a catastrophic event, P_{cat}, is a combination of the failures of the state machine, P_s; electronics failure, P_e; controller failure, P_c; and the probability of impact behind the gun, P_i. The computing cluster Monte Carlo analysis provides a means of computing the P_i term; however, further engineering analysis would be required for computing the other probabilities.

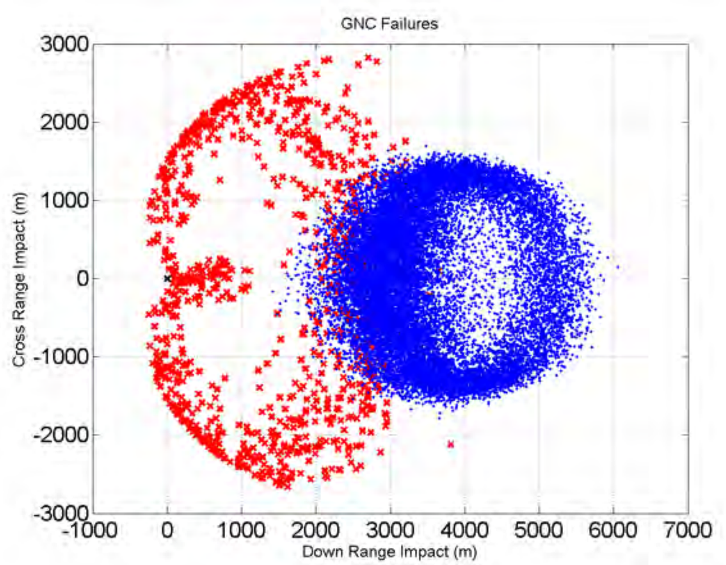

Figure 8. Failure of the GN&C system.

5. Safety Fan Analysis

To compute the safety fan, we can use the output of the computing cluster to formulate a distribution of the impact points of the projectile. This can be demonstrated through an example. For instance, if the distribution output is that of figure 7, we can look at the extreme ranges for the distribution and compute a probability distribution fit to the data. Figure 9 shows how a normal distribution can be fit to the rounds that fall short. A fit to a normal distribution yields a mean, $\mu = 2.958$ km, and a standard deviation, $\sigma = 434$ m. This method can be applied for many different distribution function and is not limited to normal distributions. With this data, we can then approximate the extreme maneuver ability across the input distributions to formulate a $6 - \sigma$ probability of impact (the lines on figure 9). The $6 - \sigma$ approach yields the probability of occurrence of 0.999999993924117, or approximately 1 in 164 million runs, sufficient enough for any experimental test. So using the example, the minimum distance the round could possibly land would be 351 m under all circumstances simulated.

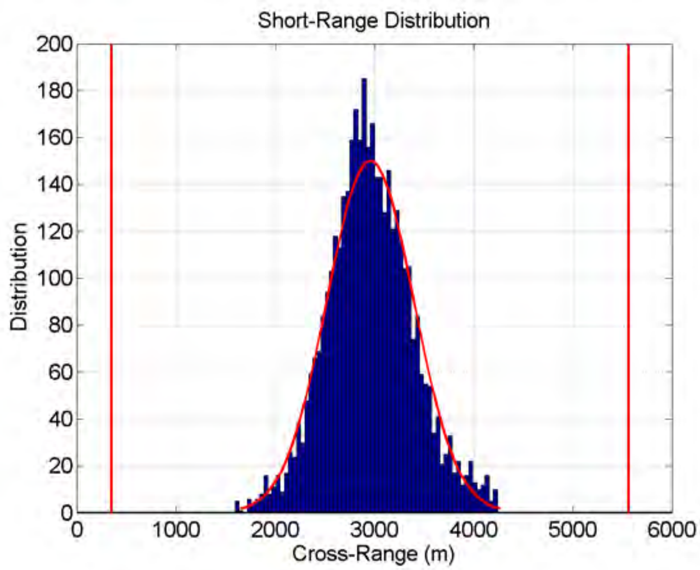

Figure 9. Short impacts histogram and fit.

6. Conclusion

This report presented a method for speeding up projectile 6DOF simulations for use during the GN&C development phase. We described the method for converting a standard Simulink$^{\mathrm{TM}}$ model into a RSim model that could be run with adequate improvement over the standard simulation mode and migrated to a standalone executable. We also covered the design of an interface for a computing cluster running a Condor scheduler. Lastly, we demonstrated the use of these methods for a safety fan calculation using 20k runs of a 6DOF running on the computing cluster.

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List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
3DOF	three-degrees-of-freedom
6DOF	six-degrees-of-freedom
APG	Aberdeen Proving Ground
ARL	U.S. Army Research Laboratory
CFD	computational fluid dynamics
FCMortar	Flight Controlled Mortar
GN&C	Guidance, Navigation, and Control
HIL	hardware-in-the-loop
M&S	modeling and simulation
MBD	Model Based Design
ODE	ordinary differential equation
PDF	probability distribution function
PIL	processor-in-the-loop
PRESIMEN	Precision Simulation Environment
RSim	Rapid Acceleration Model
RTP	Real time Parameter
RTW	Real-Time Workshop
VAPP	Very Affordable Precision Projectile

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